Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

Fermilab Users Meeting Presentation
11 June 2014

S. Ritz

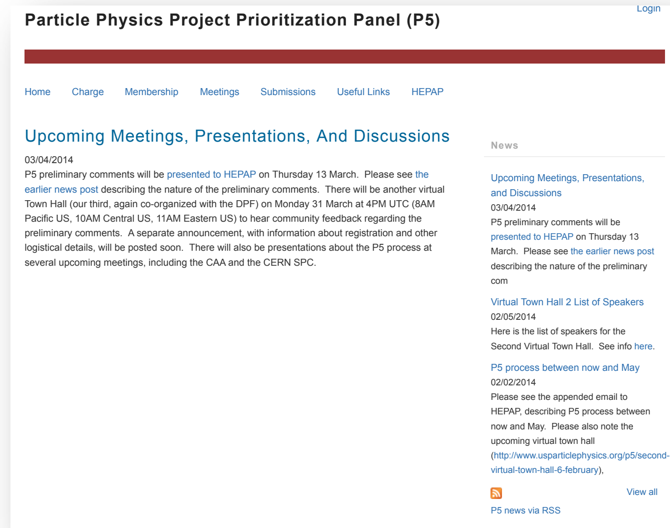
Panel Members

Hiroaki Aihara (Tokyo)
Martin Breidenbach (SLAC)
Bob Cousins (UCLA)
André de Gouvêa (Northwestern)
Marcel Demarteau (ANL)
Scott Dodelson (FNAL/ Chicago)
Jonathan Feng (UCI)
Bonnie Fleming (Yale)
Fabiola Gianotti (CERN)
Francis Halzen (Wisconsin)
JoAnne Hewett (SLAC)
Andy Lankford (UCI)
Wim Leemans (LBNL)
Joe Lykken (FNAL)
Dan McKinsey (Yale)
Lia Merminga (TRIUMF)
Toshinori Mori (Tokyo)
Tatsuya Nakada (Lausanne)
Steve Peggs (BNL)
Saul Perlmutter (Berkeley)
Kevin Pitts (Illinois)
Steve Ritz (UCSC, chair)
Kate Scholberg (Duke)
Rick van Kooten (Indiana)
Mark Wise (Caltech)

A very dedicated, hardworking panel!

Summary of P5 Process

- Meetings:
  - Face-to-face
    - Three big, open, topical meetings. Agendas and slides posted online.
    - Four additional panel face-to-face meetings.
  - Continuous work between meetings
- Large Project/Activity worksheets for all phases (R&D, construction, operations) to help ensure uniformity, data quality.
- Continuous effort to maximize community interactions, including:
  - All info available on P5 website, frequently updated with News (RSS and Twitter feeds)
  - Numerous emails, outreach to younger physicists
  - Town halls at all 3 big meetings
  - Virtual town halls (with DPF) 8 Jan, 6 Feb, 31 Mar
  - Public submissions portal
  - Many ongoing discussions and consultations
- Peer review of report draft 5-10 May



http://interactions.org/p5

- Internal deliberations worked by consensus.
- No topic or option was off the table. Every alternative we could imagine was considered.

HEPAP accepted the report on 22 May 2014

Science Drivers

- We distilled the eleven groups of physics questions from Snowmass* into five compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.
- The Science Drivers:
  - **Use the Higgs boson as a new tool for discovery**
  - **Pursue the physics associated with neutrino mass**
  - **Identify the new physics of dark matter**
  - **Understand cosmic acceleration: dark energy and inflation**
  - **Explore the unknown: new particles, interactions, and physical principles**
- The Drivers are deliberately not prioritized because they are intertwined, probably more deeply than is currently understood.
- A selected set of different experimental approaches that reinforce each other is required. Projects are prioritized.
- The vision for addressing each of the Drivers using a selected set of experiments – their approximate timescales and how they fit together – is given in the report.

* See Appendix D and http://www.slac.stanford.edu/econf/C1307292/

Particle Physics is Global

- The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere.
  - Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision.
- Strong foundations of international cooperation exist, with the Large Hadron Collider (LHC) at CERN serving as an example of a successful large international science project.
- Reliable partnerships are essential for the success of international projects. This global perspective is finding worldwide resonance in an intensely competitive field.
  - The 2013 *European Strategy for Particle Physics* report focuses at CERN on the Large Hadron Collider (LHC) program and envisions substantial participation at facilities in other regions.
  - Japan, following its 2012 *Report of the Subcommittee on Future Projects of High Energy Physics*, expresses interest in hosting the International Linear Collider (ILC), pursuing the Hyper-Kamiokande experiment, and collaborating on several other domestic and international projects.

March Preliminary Comments Presentation

Topics

- Review of the key elements of the charge; summary of P5 processes and activities since September
- Context:
  - The evolution of our field since the previous P5 report
  - Big scientific questions and drivers
  - The global nature of our field
- Key elements of strategic planning:
  - Opportunities to address the big scientific questions and how they fit together
  - Budgetary constraints compared with proposed programs
  - National planning in the global context
  - Balancing investments
- Discussion of prioritization criteria
- Steps to completion, and communication planning

March 2014 2

Discussed at length:

- **The 5 Science Drivers**
- **Global vision**
- **Criteria**
- **Budget scenario challenges**
- **Ongoing community interactions**

Recall, the Charge specifies three budget scenarios, with ten-year profiles:

A. *FY2013 budget baseline: flat for 3 years, then +2% per year.*

B. *FY2014 President's budget request baseline: flat for 3 years, then +3% per year.*

C. *Unconstrained:* projects *"…needed to mount a leadership program addressing the scientific opportunities…"*

Difference between scenarios integrated over the decade is ~$0.5B.

"***…consider these scenarios not as literal budget guidance but as an opportunity to identify priorities and make high-level recommendations.***"

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

DRAFT FOR APPROVAL Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context

Figure 1
Construction and Physics Timeline

FIGURE 1 Approximate construction (blue; above line) and expected physics (green; below line) profiles for the recommended major projects, grouped by size (Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

Neutrino Oscillation Experiments (Program)

- Short- and long-baseline oscillation experiments directly probe three of the questions of the neutrino science Driver:
  - How are the neutrino masses ordered? Do neutrinos and antineutrinos oscillate differently? Are there additional neutrino types and interactions?
- There is a vibrant international neutrino community invested in pursuing the physics of neutrino oscillations.
- The U.S. has unique accelerator capabilities at Fermilab to provide neutrino beams for both short- and long-baseline experiments, with some experiments underway, and a long-baseline site is available at the Sanford Underground Research Facility in South Dakota.
- Many of these current and future experiments and projects share the same technical challenges. Interest and expertise in neutrino physics and detector development of groups from around the world combined with the opportunities for experiments at Fermilab provide the essentials for an international neutrino program.

- **Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.**

Neutrino Oscillation Experiments (LBNF)

- The long-baseline neutrino program plan has undergone multiple significant transformations since the 2008 P5 report. Formulated as a primarily domestic experiment, the minimal CD-1 configuration with a small, far detector on the surface has very limited capabilities.
- A more ambitious long-baseline neutrino facility has also been urged by the Snowmass community study and in expressions of interest from physicists in other regions.
- To address even the minimum requirements specified above, **the expertise and resources of the international neutrino community are needed.**

- **A change in approach is therefore required**: The activity should be reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host. There should be international participation in defining the program's scope and capabilities. The experiment should be designed, constructed, and operated by the international collaboration. The goal should be to achieve, and even exceed if physics eventually demands, the target requirements through the broadest possible international participation.

Neutrino Oscillation Experiments (LBNF Requirements)

- For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.
  - By current estimates, this corresponds to an exposure of 600 kt*MW*y assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector.
- **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

These minimum requirements are not met by the current LBNE project's CD-1 minimum scope.

Neutrino Oscillation Experiments (LBNF Recommendation)

- Key preparatory activities will converge over the next few years: in addition to the international reformulation described above, PIP-II design and project definition will be nearing completion, as will the necessary refurbishments to the Sanford Underground Research Facility. Together, these will set the stage for the facility to move from the preparatory to the construction phase around 2018. The peak in LBNF construction would occur after HL-LHC peak construction.

- **Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.**

Near-term & Mid-term High-energy Colliders (LHC)

- The nearest-term high-energy collider, the LHC and its upgrades, is a core part of the U.S. particle physics program, with unique physics opportunities addressing three of the main science Drivers (Higgs, New Particles, Dark Matter).
- The Phase-2 luminosity upgrade (HL-LHC) – encompassing both the general-purpose experiments (ATLAS and CMS) and the accelerator – is required to fully exploit the physics opportunities offered by the ultimate energy and luminosity performance of the LHC.
- The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.
    - **We note that, as in the past, the contributed hardware is designed and built in the U.S.**

Near-term & Mid-term High-energy Colliders (LHC)

- The experiments and accelerator upgrades cannot occur without the unique U.S. technical capabilities (e.g. the high-field magnets necessary for the success of the project) and resources. In addition, the participation in the LHC continues to be a successful example of U.S. reliability in international partnerships, and it can serve as a stimulus and model of the great mutual benefits while further partnerships, such as for the U.S.-hosted neutrino program, are formulated.
- **Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.**

Significant Changes in Direction (1/2)

- Increase investment in construction.
  - In constrained scenarios, this implies increased fraction of budget toward construction**
- Reformulate the long-baseline neutrino program as an internationally designed and funded program, with Fermilab as host.
- Upgrade the Fermilab proton accelerator complex to produce the world's most powerful neutrino beam, redirecting former Project-X activities and temporarily redirecting some existing accelerator R&D toward this effort (a.k.a. PIP-II).

**For some history of the DOE component of the budget see http://science.energy.gov/~/media/hep/hepap/pdf/march-2013/HEPAP_Mar_2013_JS_v3b_Siegrist_DAY2_FINAL.pdf

Significant Changes in Direction (2/2)

- Proceed immediately with a broad second-generation (G2) dark matter direct detection program. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.
- Provide increased particle physics funding of Cosmic Microwave Background research and projects, as part of the core particle physics program, in the context of continued multiagency partnerships.
- Re-align activities in accelerator R&D, which is critical to enabling future discoveries, based on new physics information and long-term needs.
  - Reassess the Muon Accelerator Program (MAP) and consult with international partners on the early termination of MICE.
  - In the general accelerator R&D program, focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid- and far-term accelerators.

Scenarios B and A

- Scenario B allows for a balanced program
- The two constrained budget Scenarios differ by approximately \$30M per year until FY2018, and thereafter have a one percent escalation difference. The return on the incremental investment would be very large:
  - DESI would yield scientific returns with high impact.
  - World-leading accelerator and instrumentation development research would be retained.
  - US. research capability would be maintained, including a thriving theory program.
  - The Muon-to-electron Experiment (Mu2e) at Fermilab would be completed on time.
  - The long-baseline neutrino program would proceed without delays.
  - Third-generation dark matter direct detection capabilities would be fully developed on time.
- As valuable as each of these items is, they simply do not fit in Scenario A.

Scenario A

- The lowest budget Scenario is precarious: it approaches the point beyond which hosting a large ($1B scale) project in the U.S. would not be possible while maintaining the other elements necessary for mission success.
- Without the capability to host a large project, the U.S. would lose its position as a global leader in this field, and the international relationships that have been so productive would be fundamentally altered.

Scenario C

- The U.S. could move boldly toward development of transformational accelerator R&D.
  - Change the capability-cost curve of accelerators.
  - Newly formed HEPAP Subcommittee on Accelerator R&D to provide detailed roadmap.
  - As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.
- Should the ILC go forward, Scenario C would enable the U.S. to play world-leading roles in the detector program as well as provide critical expertise and accelerator components.
- The U.S. could offer to host a large water Cherenkov neutrino detector to complement the LBNF liquid argon detector
  - Take full advantage of the world's highest intensity neutrino beam. This approach would be an excellent example of global cooperation and planning.

Experimental and Theoretical Research

- The particle physics research program supports activities that give meaning to the data.
- Graduate students and postdoctoral researchers have essential roles in all aspects of this world-leading research. In turn, these young researchers obtain scientific and technical training. This develops the next generation of scientific leaders and provides to society a cadre of young people with extraordinary skills and experience.
- **The U.S. has leadership in diverse areas of theoretical research in particle physics. A thriving theory program is essential for both identifying new directions for the field and supporting the current experimental program**.
  - Theoretical physicists are needed for a variety of crucial activities that include taking the lead in the interpretation and synthesis of a broad range of experimental results, progress in quantum field theory and possible new frameworks for a deeper understanding of Nature, and developing new ideas into testable models.
  - Theoretical research both defines the physics drivers of the field and finds the deep connections among them.
  - As experiments have confronted the Standard Model with increasing sophistication, theoretical research has provided extraordinary advances in calculation techniques, pushing the leading edge of both mathematics and high performance computing.

Two of the Research-related Recommendations

- Particle physics is a remarkably dynamic field, with researchers nimbly changing course to invent and pursue great new opportunities. It is appropriate that priorities in the research program should be aligned with the science Drivers and the investments in projects. At the same time, it is essential to preserve a diversity of scientific approaches, support and training for young researchers, as well as leadership and forward thinking in theoretical and experimental research. It is the research program's flexibility to support new ideas and developments outside approved projects that will position the field to develop and pursue the next generation of science Drivers.
- **Recommendation 6: In addition to reaping timely science from projects, the research program should provide the flexibility to support new ideas and developments.**

- The research program is the intellectual seed corn of the field. Properly cared for, the program will yield a bounty of future discoveries and innovations within and beyond particle physics. However, the community has been coping with a sequence of recent cuts in the research program budgets, and there is a strong sense that further erosion without careful evaluation will cause great damage.
- **Recommendation 7: Any further reduction in level of effort for research should be planned with care, including assessment of potential damage in addition to alignment with the P5 vision.**

P5 Panel Perspective

- This is a challenging time for particle physics. The science is deeply exciting and its endeavors have been extremely successful, yet funding in the U.S. is declining in real terms. The report offers important opportunities for U.S. investment in science, prioritized under the tightly constrained budget scenarios in the Charge.
- We had the responsibility to make the tough choices for a world-class program under each of these scenarios, which we have done. At the same time, we felt the responsibility to aspire to an even bolder future.
- Wondrous projects that address profound questions inspire and invigorate far beyond their specific fields, and they lay the foundations for next-century technologies we can only begin to imagine. Particle physics is an excellent candidate for such investments.
- Historic opportunities await us, enabled by decades of hard work and support.
- Our field is ready to move forward.

Recent P5 Activities

- (ongoing) many consultations and discussions with community members and leaders of projects and activities in other regions
- 27 May: 90-minute briefing at the Executive Office of the President (OSTP/OMB, including the examiners for NSF and DOE and agency representatives). They were very engaged and interested.
- 28 May: Secretary Moniz briefing (30 minutes)
- 29 May: briefing and discussion with the APS Physics Policy Council. Speakers were Ritz, Lankford, and Lockyer. APS President Mac Beasley sent testimony in support of HEP for our hearing on 10 June (see below).
- 2 June: Community presentation, followed by further discussions in various venues.
- 5 June: Senate Energy and Natural Resources briefing. Pushpa is writing a summary. There were also statements of support read by Jonathan Bagger, Drew Baden, and Bob Wilson. Joe Lykken was also there and talked with staffers and others.
- 6 June: LHCP panel and presentations. Fabiola gave a great talk on future colliders. Dennis Overbye moderated a panel discussion (Ritz, Arkani-Hamed, Blazey, Bertolucci, Muryama, Roe). Andy and Jim then summed up.
- 8 June: CMS meeting in Tahoe.
- 10 June: House Energy subcommittee hearing. Nigel Lockyer, Natalie Roe, Persis Drell, and Steve Ritz were invited to testify.
- 11 June: FNAL Users meeting
- 12 June: U. Chicago physics department presentation, as well as additional meetings.
- 16 June: DOE PI meeting presentation and discussion
- 16-17 June: Andy will present to the CERN SPC
- 23-24 June: P5 presentation at the international neutrino meeting in Paris

- Other presentations are being planned, including NSAC, ECFA, Advanced Accelerator Workshop in July, BPA, AAAC, …

- There are also strong letters of support from APS President Beasley and other community organizations.
- Still early days, but far enough along that we can now say so far so good! Suggestions always welcome and needed, as usual.

Discussion

Additional Slides

Near-term & Mid-term High-energy Colliders (ILC)

- Participation by the U.S. in ILC project construction depends on a number of key factors, some of which are beyond the scope of P5 and some of which depend on budget Scenarios.
- As the physics case is extremely strong, we plan in all Scenarios for ILC support at some level through a decision point within the next five years.
    - If the ILC proceeds, there is a high-priority option in Scenario C to enable the U.S. to play world-leading roles.
    - Even if there are no additional funds available, some hardware contributions may be possible in Scenario B, depending on the status of international agreements at that time.
    - If the ILC does not proceed, then ILC work would terminate and those resources could be applied to accelerator R&D and advanced detector technology R&D.
- **Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.**

Additional Project Concepts

- Concepts to address various aspects of neutrino oscillation physics via alternative approaches were considered, including
  - RADAR
  - CHIPS
  - DAEdALUS and IsoDAR
  - LAr1
  - PINGU
  - NuSTORM
- These cannot go forward as major projects at this time, due to concept maturity and/or program cost considerations. However, further development of PINGU is recommended, and IsoDAR (precursor to DAEdALUS) should be considered in the context of a short-baseline oscillation program.
- Similarly, P5 heard presentations about several other concepts for projects whose ultimate construction scope would be large but whose near-term request for R&D funding is small. These include the Storage Ring Proton EDM Experiment and NNbarX, both of which address P5 Drivers. Development has not yet advanced to a point at which it would be possible to consider recommendations to move forward with any of these projects. The R&D for these projects would fit as candidates in the small projects portfolio, with the path to eventual implementation presumably being among the evaluation criteria.

MAP

- Neutrino factories based on muon storage rings could provide higher intensity and higher quality neutrino beams than conventional high power proton beams on targets. This concept would be attractive for an international long-baseline neutrino program offering more precise and complete studies of neutrino physics beyond short-term and mid-term facilities.
- Muon colliders can reach higher energies than e^+e^- accelerators, but have many technical challenges. Addressing all of the necessary challenges would require a very strong physics motivation based on results from ongoing or future accelerators.
- The **Muon Accelerator Program (MAP)** currently aims at technology feasibility studies for far-term muon storage rings for neutrino factories and for muon colliders, including the **Muon Ionization Cooling Experiment (MICE)** at the Rutherford Appleton Laboratory.
- The large value of $\sin^2(2\theta_{13})$ enables the next generation of oscillation experiments to use conventional neutrino beams, pushing the time frame when neutrino factories might be needed further into the future, and the small Higgs mass enables study at more technically ready e+e- colliders, reducing the near-term necessity of muon colliders.

- **Recommendation 25: Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.**

ORKA

- The ORKA kaon experiment would provide an opportunity to make measurements of a process with very small theoretical uncertainties in the Standard Model with discovery potential for multi-TeV scale new physics. It has the potential for significant improvement over CERN experiment NA62, which uses a complementary technique and which has a head start.
- The suite of measurements with ORKA would provide excellent training for students and postdocs, and this mid-size project offers additional balance to the large-scale projects in the field.
- Unfortunately, due to resource constraints and anticipated conflicts with the highest priority items in the Fermilab program, P5 cannot recommend moving ahead with ORKA at this time.

Summary (1/2)

- A vision that starts from the science Drivers, driven by community discussions and inputs, with criteria to make tough choices and develop a program.
- The enormous physics potential of the LHC, entering a new era with its planned high-luminosity upgrades, should be fully exploited.
- The U.S. should host a world-leading neutrino program.
  - An optimized set of short- and long-baseline neutrino oscillation experiments, with the long-term focus on the Long Baseline Neutrino Facility (LBNF).
  - The Proton Improvement Plan (PIP-II) project at Fermilab would provide the needed neutrino physics capability.
- Large projects are ordered by peak construction time: the Mu2e experiment completion, the high-luminosity LHC upgrades, and LBNF.
  - Based on budget constraints, physics needs, and readiness.
- The interest expressed in Japan in hosting the International Linear Collider (ILC) is an exciting development.
  - Participation by the U.S. in project construction depends on a number of important factors, some of which are beyond the scope of P5 and some of which depend on budget Scenarios.
  - As the physics case is extremely strong, all Scenarios include ILC support at some level through a decision point within the next 5 years.

Summary (2/2)

- Medium and small projects in areas especially promising for near-term discoveries and in which the U.S. is in a leadership position, should move forward under all budget scenarios.
  - Second- and third-generation dark matter direct detection experiments, the particle physics components of the Large Synoptic Survey Telescope (LSST) and cosmic microwave background (CMB) experiments, and a portfolio of small neutrino experiments.
  - Another important project of this type, the Dark Energy Spectroscopic Instrument (DESI), would also move forward, except in the lowest budget Scenario.
- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe.
  - In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field.
  - This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.
- Specific investments should be made in essential accelerator R&D and instrumentation R&D. The field relies on its accelerators and instrumentation and on R&D and test facilities for these technologies.

Neutrino Oscillation Experiments (Concepts)

- RADAR and CHIPS are both ideas for new detectors exploiting the existing NuMI beamline to improve knowledge of oscillation parameters. The RADAR proposal is to build a liquid argon TPC at the Ash River site, thereby offsetting R&D costs for LBNF. CHIPS proposes a large water Cherenkov detector in a water-filled mine pit, first at a NuMI off-axis location, and possibly later as an off-axis LBNF detector. Although one might gain some incremental sensitivity beyond NOvA and T2K in the shorter term with RADAR or CHIPS, the CP and mass hierarchy reach is reduced compared to that of the LBNF configuration, and these experiments are less capable for proton decay, atmospheric neutrinos, and SN burst neutrinos. A strategy focusing resources on moving ahead as fast as possible on LBNF is therefore favored.

- DAEdALUS is a different approach to the measurement of δ_{CP}, using multiple high-power cyclotrons to generate a large neutrino flux from pion decay-at-rest at a large water Cherenkov or liquid scintillator detector. The concept still requires significant development, and a suitable large-detector target has not yet been selected. IsoDAR is a proposed precursor phase to DAEdALUS with a well-defined short-baseline neutrino-oscillation physics program using cyclotron-produced ^{8}Li decay at rest. IsoDAR should be considered in the context of a short-baseline oscillation program.

Neutrino Oscillation Experiments (Concepts)

- LAr1 is a mid-scale short-baseline accelerator-based experiment to address both the neutrino and anti-neutrino SBL anomalies. An appropriate combination of smaller near-term projects may accomplish most of these goals at much lower cost, so proceeding with LAr1 is not recommended at this time.

- PINGU, an infill array concept at the IceCube facility, may also have the interesting potential to determine the neutrino mass hierarchy using atmospheric neutrinos sooner than other competing methods, as well as have sensitivity to low-mass WIMP dark matter. The details of the experiment are still under development, and we encourage continued work to understand systematics. PINGU could play a very important role as part of a larger upgrade of IceCube, or as a separate upgrade, but more work is required.

- NuSTORM is a proposal for a small muon storage ring to produce ~GeV neutrinos and antineutrinos with the advantage of a precisely known flux. The facility would also serve as an intense source of low-energy muons and serve as a technology demonstrator for a future neutrino factory. The physics reach of this program includes sensitive sterile neutrino searches and precision neutrino cross-section measurements. Although the concept is attractive as a first step towards a neutrino factory and as a means to reduce the beam-related systematic errors for LBNF, the high cost makes it impossible to pursue at the same time as PIP-II and LBNF, which are the primary objectives.

Neutrino Oscillation Experiments (PIP-II)

- The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure. The project has already attracted interest from several potential international partners.
- **Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.**

Program-wide Recommendations (Building)

- Unlike other regions in the world, in recent years the U.S. particle physics program has not invested substantially in construction of experimental facilities. Addressing the Drivers in the coming and subsequent decades requires renewed investment in projects. In constant or near-constant budgets, this implies an increase in the fraction of the budget that is invested in new projects, which is currently approximately 16% (and was even lower before).

- **Recommendation 5: Increase the budget fraction invested in construction of projects to the 20%–25% range.**

- This represents a large commitment to building new experiments, which we see as essential. Increasing the project fraction would necessarily entail judicious reductions in the fractions of the budget invested in the research program and operations. (The three main budget categories are project construction, the research program, and operations.)

- In addition, for the research program, which has seen reductions in recent years, flat-flat budgets are substantially detrimental over time due to escalation of real costs. To limit reductions in research program funding, we adopted a guideline that its budget fraction should be >40% in our budget planning exercises.

Near-term & Mid-term High-energy Colliders (ILC)

- **The interest expressed in Japan in hosting the International Linear Collider (ILC), a 500 GeV e^+e^- accelerator upgradable to 1 TeV, is an exciting development.**
  - Significantly extended discovery potential.
  - The ILC would follow the HL-LHC as a complementary instrument for performing these studies in a global particle physics program, providing a stream of results exploring three of our Drivers for many decades.
- The U.S. has played key roles in the design of the ILC accelerator, including leadership in the Global Design Effort. Continued intellectual contributions to the accelerator and detector design are still necessary to enable a site-specific bid proposal, which would take advantage of unique U.S. accelerator physics expertise such as positron source design, beam delivery, superconducting RF, and the accelerator-detector interface.
- Particle physics groups in the U.S. also led the design of one of the two ILC detector concepts. The required capabilities of the detectors to perform precision measurements are challenging and need continued technology development.
- Support for both the accelerator and advanced detector development efforts would enhance expertise and ensure a strong position for the U.S. within the ILC global project.

Near-term & Mid-term High-energy Colliders (LHC)

- The LHC program is a model for successful international science projects, and the LHC experiments are a model for international collaborations. The U.S. contingents in ATLAS and CMS form the largest national groups in both experiments and are the largest fraction of the U.S. particle physics community.
- The U.S. LHC program is a successful interagency partnership of the NSF Physics Division and the DOE Office of High Energy Physics, with each agency supporting numerous research groups in distinctive roles in the experiments, including collaboration leadership.
  - Continuing the successful inter-agency collaboration, with their distinctive roles and contributions, in the upgrade era would bring benefits to DOE and NSF, as well as to their respective research communities.

Use the Higgs boson as a new tool for discovery

- The recently discovered Higgs boson is a form of matter never before observed.
  - What principles determine its effects on other particles? How does it interact with neutrinos or with dark matter? Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others?
  - The Higgs boson offers a unique portal into the laws of Nature, and it connects several areas of particle physics. Any small deviation in its expected properties would be a major breakthrough.

- The full discovery potential of the Higgs will be unleashed by percent-level precision studies of the Higgs properties. The measurement of these properties is a top priority in the physics program of high-energy colliders.
  - The Large Hadron Collider (**LHC**) will be the first laboratory to use the Higgs boson as a tool for discovery, initially with substantial higher energy running at 14 TeV, and then with ten times more data at the High-Luminosity LHC (**HL-LHC**). The HL-LHC has a compelling and comprehensive program that includes essential measurements of the Higgs properties.
  - An e^+e^- collider can provide the next outstanding opportunity to investigate the properties of the Higgs in detail. The International Linear Collider (**ILC**) is the most mature in its design and readiness for construction. The ILC would greatly increase the sensitivity to the Higgs boson interactions with the Standard Model particles, with particles in the dark sector, and with other new physics. The ILC will reach the percent or sub-percent level in sensitivity.
  - Longer-term future-generation accelerators bring prospects for even better precision measurements of Higgs properties and discovery potential.

Pursue the physics associated with neutrino mass

- Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades, with a promising future of continued discovery.
- Many aspects of neutrino physics are puzzling. Powerful new facilities are needed to move forward, addressing:
  - What is the origin of neutrino mass? How are the masses ordered (referred to as mass hierarchy)? What are the masses? Do neutrinos and anti-neutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles?
- The U.S. is well positioned to host a world-leading neutrino physics program, which includes an optimized set of short- and long-baseline neutrino oscillation experiments
  - The long-term focus is a reformulated venture referred to here as the Long Baseline Neutrino Facility (**LBNF**), an internationally designed, coordinated, and funded program with Fermilab as host.
  - LBNF would combine a high-intensity neutrino beam and a large-volume precision detector sited underground a long distance away to make accurate measurements of the oscillated neutrino properties. This large detector would also search for proton decay and neutrinos from supernova bursts.
- A powerful, wideband neutrino beam would be realized with Fermilab's **PIP-II** upgrade project, which provides very high intensities in the Fermilab accelerator complex.
- Cosmic surveys and a variety of other small experiments will also make important progress in answering these questions.

Identify the new physics of dark matter

- Astrophysical observations imply that the known particles make up only about one-sixth of the total matter in the Universe. The rest is dark matter (DM). The properties of dark matter particles, which are all around us, are largely unknown.
- Experiments are poised to reveal the identity of dark matter, a discovery that would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe. There are many well-motivated ideas for what dark matter could be, including
  - weakly interacting massive particles (WIMPs), axions, and new kinds of neutrinos.

- Direct detection experiments are sensitive to dark matter interactions with ordinary particles in the laboratory and will follow a progression from currently proposed second-generation (**DM G2**) experiments to much larger third-generation (**DM G3**) experiments.
- Indirect detection experiments, such as the **CTA** gamma-ray observatory, can spot the particle debris from interactions of relic dark matter particles in space. Cosmic surveys are sensitive to dark matter properties through their effects on the structures of galaxies.
- Experiments now at the LHC and eventually at future colliders seek to make dark matter particles in the laboratory for detailed studies.

Understand cosmic acceleration: dark energy and inflation

- With the telescopes that peer back in time and high-energy accelerators that study elementary particles, scientists have pieced together a story of the origin and evolution of the Universe. An important part of this story is the existence of two periods during which the expansion of the Universe accelerated.
  - A primordial epoch of acceleration, called inflation, occurred during the first fraction of a second of existence. The cause is unknown -- fundamentally new physics at ultra-high energies. A second distinct epoch of accelerated expansion began more recently and continues today, presumed to be driven by some kind of dark energy, which could be related to Einstein's cosmological constant, or driven by a different type of dark energy that evolves with time.
- Understanding inflation is possible by measuring the characteristics of two sets of primordial ripples: those that grew into the galaxies observed today, and gravitational waves, undulations in space and time that may have been observed just months ago by the BICEP2 telescope looking at the cosmic microwave background (CMB). Current CMB probes will lead to a **Stage 4 Cosmic Microwave Background (CMB-S4)** experiment, with the potential for important insights into the ultra-high energy physics that drove inflation.
- Understanding the second epoch requires better measurements:
  - The Dark Energy Spectroscopic Instrument (**DESI**) can determine the properties of dark energy to the percent level over the course of billions of years. The Large Synoptic Survey Telescope (**LSST**), measuring the positions, shapes, and distances of billions of galaxies, will perform many separate tests of the properties of dark energy.
  - Together, they can also probe the possibility that, instead of dark energy, new laws beyond those introduced by Einstein are responsible for the recent cosmic acceleration.

Explore the unknown: new particles, interactions, and physical principles

- There are clear signs of new phenomena awaiting discovery beyond those of the other four Drivers. Particle physics is a discovery science defined by the search for new particles and new interactions, and by tests of physical principles.

- Producing new particles at colliders:
  - Well-motivated extensions of the Standard Model predict that a number of such particles should be within reach of LHC. HL-LHC will extend the reach for new particles that could be missed by LHC. In the event that one or more new particles are already discovered during LHC running, HL-LHC experiments will be essential to reveal the identities and underlying physics of these particles.

- Detecting the quantum influence of new particles:
  - The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena, using different kinds of particles as probes that are sensitive to different types of new particles and interactions. Some notable examples are a revolutionary increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus **Mu2e** (Fermilab) and **COMET** (J-PARC), further studies of rare processes involving heavy quarks or tau leptons at **Belle II** (KEK) and **LHCb** (LHC), and a search for proton decay using the large neutrino detectors of the **LBNF** and proposed **Hyper-K** experiments.

- Future Opportunities:
  - In the longer term, **very high-energy e^+e^- colliders** and **very high-energy proton colliders** could extend the search for new particles and interactions, as well as enable precision studies of the Higgs boson and top quark properties . Upgrades at Fermilab (**PIP-II** and additional improvements) will offer further opportunities to detect the influence of new particles in rare processes.

Neutrino Oscillation Experiments (Short Baseline)

- Hints from short-baseline experiments suggest possible new non-interacting neutrino types or non-standard interactions of ordinary neutrinos. These anomalies can be addressed by proposed experiments with neutrinos from radioactive sources, pion decay-at-rest beams, pion and kaon decay-in-flight beams, muon-decay beams, or nuclear reactors.
- A judiciously selected subset of experiments can definitively address the sterile-neutrino interpretation of the anomalies and potentially provide a platform for detector development and international coordination toward LBNF.
  - These small-scale experiments are in addition to the small projects portfolio described above.
  - The short-term short-baseline (SBL) science and detector development program and the long-term LBNF program should be made as coherent as possible in an optimized neutrino program.
- **Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

Enabling R&D

- Advances in accelerators, instrumentation, and computing are necessary to enable the pursuit of the Drivers. Greater demands are being placed on the performance in all three areas, at reduced cost, necessitating continued investments in R&D.
- The DOE General Accelerator R&D (GARD) program and Accelerator R&D Stewardship program, as well as the new NSF Basic Accelerator Science program, form the critical basis for both long- and short-term accelerator R&D, enriching particle physics and other fields.
- **Superconducting radio-frequency accelerating cavities, high-field superconducting magnets, advanced particle acceleration techniques,** and other technologies are being developed for the required higher performance and lower cost of future accelerator concepts.
- Directed R&D programs, such as for the LHC Accelerator Research Program (**LARP**) and the Fermilab Proton Improvement Plan-II (**PIP-II**), will enable the next generation of accelerators. State-of-the-art test facilities at the national labs support activities on advanced accelerator R&D by both university and laboratory scientists.
- New particle detection techniques and instrumentation developments will provide the higher resolutions and higher sensitivities necessary to address the ever more challenging demands of future accelerator-based, underground, and cosmic particle physics experiments. Meanwhile, new computing and software techniques for acquiring, processing, and storing large data sets will empower future experiments to address not only more challenging questions, but also a broader sweep of questions.

Criteria

- **Program optimization criteria**
  - **Science**: based on the Drivers, assess where we want to go and how to get there, with a portfolio of the most promising approaches.
  - **International context**: pursue the most important opportunities wherever they are, and host world-leading facilities that attract the worldwide scientific community; duplication should only occur when significant value is added or when competition helps propel the field in important directions.
  - **Sustained productivity**: maintain a stream of science results while investing in future capabilities, which implies a balance of project sizes; maintain and develop critical technical and scientific expertise and infrastructure to enable future discoveries.
- **Individual project criteria**
  - **Science:** how the project addresses key questions in particle physics, the size and relevance of the discovery reach, how the experiment might change the direction of the field, and the value of null results.
  - **Timing**: when the project is needed, and how it fits into the larger picture.
  - Uniqueness: what the experiment adds that is unique and/or definitive, and where it might lead. Consider the alternatives.
  - **Cost vs. value**: the scope should be well defined and match the physics case. For multidisciplinary/agency projects, distribution of support should match the distribution of science.
  - **History and dependencies**: previous prioritization, existing commitments, and the impacts of changes in direction.
  - **Feasibility**: consider the main technical, cost, and schedule risks of the proposed project.
  - **Roles**: U.S. particle physics leadership, or participation, criticality, as well as other benefits of the project.

Multidisciplinary Aspects

- Multidisciplinary connections are of great importance to particle physics. For example, the study of the particle physics of dark energy and inflation is performed by astrophysical techniques employing the detector technologies and computing techniques of particle physics. The research can also provide information on neutrino properties.
- In a different manner, studies traditionally carried out by nuclear physics to determine if the neutrino is its own antiparticle inform the particle physics campaign to address the neutrino science Driver.
- The support from different agencies, linked by the multidisciplinary nature of the science, enables new capabilities of mutual benefit.
- For multidisciplinary projects that receive particle physics funding, our criteria include a check that the distribution of support reflects the distribution of anticipated science topics and that particle physicist participation is necessary for project success. Similar criteria were developed and used by the 2009 PASAG panel.

Executive Summary Introduction

- Particle physics explores the fundamental constituents of matter and energy. It reveals the profound connections underlying everything we see, including the smallest and the largest structures in the Universe.
- The field is highly successful. Investments have been rewarded recently with discoveries of the heaviest elementary particle (the top quark), the tiny masses of neutrinos, the accelerated expansion of the Universe, and the Higgs boson.
- Current opportunities will exploit these and other discoveries to push the frontiers of science into new territory at the highest energies and earliest times imaginable.
- For all these reasons, research in particle physics inspires young people to engage with science.

Benefits and Broader Impacts

- Particle physics shares with other basic sciences the need to innovate, invent, and develop technologies to carry out its mission. Advanced particle accelerators, cutting-edge particle detectors, and sophisticated computing techniques are the hallmarks of particle physics research.
- This dedicated research has benefited tremendously from progress in other areas of science to advance the current state of technology for particle physics. In return, developments within the particle physics community have enabled basic scientific research and applications in numerous other areas. This broad, connected scientific enterprise provides tremendous benefits to society as a whole.
- The report summarizes many topics including:
  - Materials science
  - Medical imaging and therapy
  - National Security
  - Computing
  - Bringing to life the earliest audio recordings
  - Neuroscience
- The benefits of these connections go in both directions!

Also see the report by the Task Force on *Tools, Techniques, and Technology Connections of Particle Physics*, to be posted soon on the HEPAP site

Thanks!

- Our community's passion, dedication, and entrepreneurial spirit have been inspirational.
- To our colleagues across our country and around the world, we say a heartfelt thank you. Every request we made received a thoughtful response, even when the requests were substantial and the schedules tight. A large number of you submitted inputs to the public portal, which we very much appreciated.

The report includes 29 recommendations. Only the main points can be summarized here, so please read the full report for the important details.